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<b>13. SUPPLEMENTARY NOTES</b> The information contained herein has been derived and determined through best practice and adherence to the highest levels of ethical, scientific, and engineering investigative principles. The reported results, their interpretation, and any opinions expressed therein, remain those of the authors and do not represent, or otherwise reflect, any official opinion or position of Department of National Defence or the Government of Canada.				
<b>14. ABSTRACT</b> Air combat maneuvering produces frequent, repetitive excursions to headward acceleration (+Gz) but little is known about physiologic tolerance to successive +Gz exposures. Human responses to simulated air combat maneuvering (SACM) were measured with SACM comprised of 10 repetitive cycles of moderate +Gz loads in two investigations, on a human centrifuge (N=13), and an electronic tilt-table (N=15), respectively. Physiologic responses (blood pressure, visual field, head-level blood content) were significantly improved in cycles 2-10 compared to cycle 1 indicating +Gz tolerance increased approximately 0.4 Gz (range 0.3 - 0.6 Gz depending on SACM type and test facility). The gains are attributed to enhanced vascular resistance. Therefore, a pilot's physiologic tolerance is not expected to decrease due to repetitive +Gz during aerial combat engagement. Anti-G straining maneuvers were not studied and could produce secondary effects in such environments.				
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## FINAL REPORT

AWARD #: N00014-01-1-0044

PRINCIPAL INVESTIGATOR: Fred Buick, PhD

INSTITUTION: Defence Research and Development Canada - Toronto, Canada  
(formerly Defence and Civil Institute of Environmental Medicine)

PROJECT TITLE: G-Tolerance in Acute, Repetitive Acceleration Conditions  
Relevant to Air Combat Maneuvering

AWARD PERIOD: 1 October 2000 - 30 September 2003

OBJECTIVES: Air combat maneuvering produces frequent, repetitive excursions to high headward acceleration (+Gz) that reduce head-level blood pressure. Severe blood pressure decrease could lead to unconsciousness. The cardiovascular response to a single +Gz exposure is well understood but little is known about human tolerance to acute, successive +Gz exposures. The question posed was, does a pilot's +Gz tolerance change during the course of an aerial combat engagement? If +Gz tolerance is reduced due to repetitive +Gz exposure, the risk of losing consciousness would be increased.

Specific objectives: (a) to measure human physiologic relaxed +Gz tolerance over a set of acute, repeated +Gz exposures and compare it with tolerance in the initial exposure; and (b) to determine the physiologic mechanisms leading to the observations resulting from objective 1.

APPROACH: Human physiologic responses to simulated air combat maneuvering (SACM) were measured in separate centrifuge and tilt-table investigations. The SACM consisted of repetitive cycles of moderate +Gz loads.

In Investigation 1, thirteen volunteers<sup>1</sup> rode a human centrifuge programmed for ten cycles (C1 to C10) comprised of rapid +Gz onset, a plateau, offset, and a pause (Figure 1). +Gz duration in air combat varies and cardiovascular reflexes have different time courses, therefore SACM with four types of +Gz-time profiles were used:

SS: short (S: 8 sec) +Gz plateau with short (S: 1 sec) +Gz pause;

SL: short (S: 8 sec) +Gz plateau with long (L: 15 sec) +Gz pause;

LS: long (L: 20 sec) +Gz plateau with short (S: 1 sec) +Gz pause;

LL: long (L: 20 sec) +Gz plateau with long (L: 15 sec) +Gz pause.

The +Gz plateaus were performed at the subject's maximal relaxed tolerance level determined during training sessions on the centrifuge. The +Gz pause level was +1.4 Gz. The total times for SS, SL, LS, and LL were 135, 275, 255, and 395 sec, respectively. No anti-G suits or muscular straining maneuvers were used that would have masked the underlying cardiovascular response.

Investigation 2 was conducted on a tilt-table so that cardiovascular measurements not possible on a centrifuge could be made. Fifteen volunteers were exposed to ten tilting cycles beginning at 45 degrees head-down position for either 3 or 15 sec, then tilted to the 75 degrees head-up position for 20 sec. These tilt positions (referenced to horizontal) created -0.71 and +0.96 Gz, respectively.

ACCOMPLISHMENTS: The SACMs in Investigation 1 used the following +Gz plateau levels: +5.0 Gz (1 subject); +3.5 Gz (6 subjects); +3.0 Gz (5

<sup>1</sup> This study, approved by DRDC's Human Research Ethics Committee, was conducted in conformity with the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans.

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subjects); +2.5 Gz (1 subject). All subjects reported clear cognition throughout all runs.

The physiologic severity of the +Gz load is expressed by the extent of the reactions. In C1, minimum head-level mean arterial pressure decreased to 30% of normal and maximum heart rate increased to 142% of normal. At least 90% of the visual field was lost as rated by the subjects. The physiologic responses were statistically less severe beginning with C2. Blood pressure decreased to only 42% (average 40% over C1-10). Heart rate reduced to 132% of normal. Visual field loss was approximately 50% (Figure 2). These improvements were supported by measurements of blood content at the level of the ear. The rate of blood pressure fall was also slowed, the nadir developing in 7.2 sec in C1 and then in approximately 8.9 sec for the rest of the SACM.

Although +Gz level was constant across cycles for a given SACM, reactions from C2 forward appeared physiologically as if they were being produced at lower +Gz levels. The "as if Gz" was calculated (from regressions of Gz and physiologic reactions for each subject) and the difference between this level and the SACM +Gz level quantified the improvement in +Gz tolerance (GTOL). At C2, GTOL increased by an average 0.35 Gz over C1. The average GTOL increase was 0.40 Gz over C2-C10. The duration between cycles had a significant effect with GTOL increases of 0.53 and 0.27 Gz produced with short and long duration +Gz pauses, respectively.

In Investigation 2, despite the smaller +Gz magnitude and hence less difference between lowest and greatest Gz level within a cycle, the observations supported the findings from Investigation 1 in the centrifuge. In C1, minimum carotid-level mean arterial pressure decreased by 20 mm Hg, but by only 10 mm Hg over C2-10. Heart rate was approximately 9 bpm less in the subsequent cycles compared to C1. No measurement equivalent to +Gz tolerance on the centrifuge can be made on the tilt-table, but the blood pressure increases translate into a tolerance gain of approximately 0.6 Gz.

In the early part of the upright position of C1 tilt, forearm blood flow was elevated at 130% of baseline measured pre-tilt. For the rest of the SACM, this was reduced to an average of 84%. Simultaneously, an index for total peripheral resistance significantly increased by mean of 2.4 mm Hg/L/min for C2-10 compared to C1.

Common to the repetitive cycles on both the centrifuge and the tilt-table was the attenuation of extremes of physiologic responses. The reduced fall in minimum blood pressure with the upper +Gz level of the SACM was described above. After reaching the lower level of Gz from the higher level, blood pressure increased less beginning with C2. Thus the wide swings in blood pressure during C1 were narrowed in subsequent cycles.

Increased +Gz, whether produced in-flight, on a centrifuge, or because of position changes on a tilt-table, widens the vertical pressure gradient between heart and head causing the carotid baroreceptors to defend blood pressure by sympathetically activating increases in heart rate, cardiac contractility, vasoconstriction and venoconstriction. Since the minimum blood pressure did not decrease as low in subsequent +Gz cycles, even greater reflexive compensatory reactions are believed to explain the increased +Gz tolerance. Once achieved, there is reduced need for elevating heart rate as observed in the current studies. Our indirect assessment of stroke volume (via stroke index and pulse pressure) and contractility (via Heather index and left ventricular ejection time) leave inconclusive the contribution of cardiac factors to the increase in +Gz tolerance.

Several observations in the current studies strongly suggest that vasoconstriction was enhanced: (a) reduction in forearm blood flow; (b) increase in total peripheral resistance; (c) small but consistent increase in a particular phase of the valsalva test immediately after repetitive tilt; and (d) consistent increase in diastolic blood pressure after the first cycle in both studies. Enhanced vasoconstriction could occur by: (a) central resetting of the baroreflex; and/or (b) increased short-term hormonal activity (norepinephrine, epinephrine, and to a lesser degree angiotension, and vasopressin). Also deserving consideration would be the extent to which any mechanism is "carried over" from previous cycles as compared to a heightened reaction to a given cycle. Regardless of the mechanism contributing to the increased +Gz tolerance, the effect is stronger when the period between +Gz cycles is brief. +Gz plateau duration made no difference. Therefore, it seems the time reflexes are switched off is more important to GTOL increases than time switched on.

Fatigue or maladaptation of reflexes are possible threats in sustained +Gz exposures, or in acute repetitive exposure, but not over the durations (< 7 min) and +Gz levels ( $\leq +5$  Gz) used in the current study.

Figure 1. Sections of two SACMs to +3.5 Gz showing three cycles with short +Gz plateau - long +Gz pause (SL) and long +Gz plateau - short +Gz pause (LS).

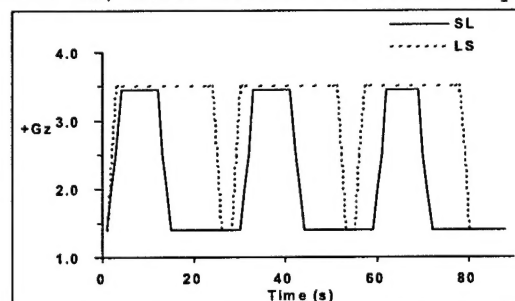
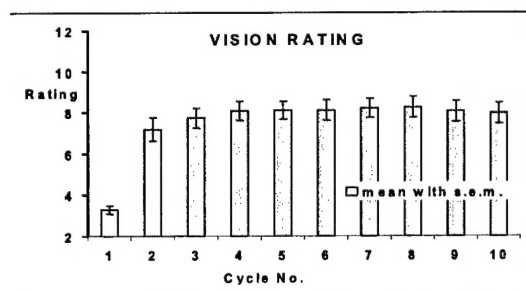


Figure 2. Vision at worst level during +Gz plateau of 10 successive cycles. Vision ratings are averaged over the four types of SACMs conducted in the human centrifuge. Clear peripheral + clear central vision = 12; complete peripheral + complete central vision loss = 2 on rating scale.



Following are perspectives on the importance of the +Gz tolerance increase (0.3 - 0.5 Gz depending on SACM type) after the initial cycle:

1. With scant evidence available, it was hypothesized that +Gz tolerance might decrease. The observation of increased tolerance is significant because it means the risk for unconsciousness in flight is not increased.
2. Unprotected centrifuge riders, and presumably also pilots, experience loss of the peripheral visual field at mean 3.1 Gz above normal gravity. Acute repetitive exposure would physiologically increase tolerance by 13%, an amount of practical importance.
3. +Gz tolerance is 1.9 Gz greater with slow onset, compared to rapid onset, +Gz profiles in the centrifuge. Repetitive rapid onset +Gz cycles elevate +Gz tolerance by 0.4 Gz relative to one cycle. Both are physiologically-developed increases in tolerance, however, slow +Gz onset profiles have little relevance to tactical flight maneuvers.
4. The properly performed anti-G straining maneuver during tactical missions can add 4 Gz to +Gz tolerance. If 0.4 Gz GTOL increase

can reduce the muscular straining requirement by 10%, delaying any associated fatigue during air combat maneuvers would be significant.

CONCLUSIONS:

1. Human physiologic relaxed +Gz tolerance increases with acute repetitive 20 sec +Gz exposures compared to the initial exposure.
2. In repetitive +Gz exposures, physiologic +Gz tolerance is greater with 1 sec compared to 15 sec intervals between +Gz cycles.
3. Vascular peripheral resistance is increased after the first +Gz exposure and most likely explains the increased +Gz tolerance.
4. Contrary to the original hypothesis, it is projected that a pilot's physiologic tolerance will not decrease due to repetitive +Gz during aerial combat engagement. Excluded are considerations such as secondary effects of any anti-G straining maneuvers (e.g. muscle fatigue, heat accumulation).

SIGNIFICANCE: (a) Pilots' physiologic +Gz tolerance does not deteriorate during air combat engagement. However, their +Gz tolerance will be lowest during the first high +Gz exposure. The carryover effect of any +Gz warmup turns performed minutes earlier is likely to be minimal. (b) The capacity for acute, cardiovascular and reflexive adjustments is important to overcoming repetitive hypotensive stress. (c) Because of different physiologic responses before and after the initial 2-3 cycles of SACM, acute repetitive +Gz exposures should not be used for verification measurements within a single session.

PATENTS: None.

AWARDS: Lalande S. Recipient of Young Investigator Award presented by Space Medicine Branch at Aerospace Medical Association, 73rd Annual Scientific Conference, Montreal, Canada, May 2002 for paper "Improved +Gz Tolerance In Short-Term, Repetitive Exposures To Acceleration".

PUBLICATIONS AND ABSTRACTS

Lalande S. and F Buick. Improved +Gz Tolerance In Short-Term, Repetitive Exposures To Acceleration [Abstract]. Presentation at Aerospace Medical Association, 73rd Annual Scientific Conference, Montreal, Canada, May 2002.

Lalande S. Improved Human +Gz Tolerance in Acute, Repetitive Exposures to Acceleration. Master of Science Thesis, Graduate Department of Exercise Sciences, University of Toronto, 2002.

Urquhart N. The Cardiovascular Response to Acute, Repeated Orthostatic Stress. Master of Science Thesis, Graduate Department of Exercise Sciences, University of Toronto, 2003.

Lalande S. and F. Buick. Increased +Gz tolerance in acute, repetitive exposure to acceleration. Manuscript submitted for publication, revised 2004.

Urquhart N, F Buick, and L Goodman. Cardiovascular Response to Acute, Repetitive Orthostatic Stress Relevant to Air Combat Maneuvering [Abstract]. Presentation at Aerospace Medical Association, 75th Annual Scientific Conference, Anchorage, Alaska, May 2004.

Urquhart N, F Buick, and L Goodman. Cardiovascular response to acute, repetitive orthostatic stress relevant to air combat maneuvering. Manuscript in preparation for journal publication, 2004.